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BOLTED CONNECTIONS - RESEARCH

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STRUCTURAL DIVISION

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BOLTED CONNECTIONS—RESEARCH

W. H. Munse,[1] A.M. ASCE

SYNOPSIS

The introduction of the high-strength bolt as a structural connector has made it possible to produce structural joints which are superior to and often more economical than comparable riveted joints. However, to obtain full benefit from the use of these bolts it is necessary that they be installed with a high initial tension. The reasons for and the effects of this high tension are discussed herein on the basis of previous data as well as the results of static and fatigue tests which have been conducted recently on bolts and bolted connections subjected to shear and tensile loadings.

INTRODUCTION

Seldom, if ever, has a new structural connector received such rapid and wide-spread acceptance as the high-strength bolt;[2] within a few years, the high-strength bolt has moved from the structural research laboratory into general acceptance in the field. This acceptance is based on the economy as well as the superior behavior obtained in both the field and the laboratory. In the field tests, the bolts have been used as replacements in connections in which rivets would periodically work loose. In the laboratory, a great deal of effort has been expended in studying the fundamental behavior of bolted joints and the conditions necessary for the most efficient use of the materials in such joints. The results of these studies have all been extremely promising.

The initial impetus for this work came from Professor W. M. Wilson in 1938 when he found that high-strength bolts tightened sufficiently to eliminate slip in a structural joint did not fail in fatigue.(1) [3] The next step in the development of the high-strength bolt as a fastener did not take place until 1945 when the late Professor G. A. Maney began preliminary studies on the problem.(10) In the Spring of 1947, the Research Council on Riveted and Bolted Structural Joints was formed and began a number of studies at the University of Illinois on joints assembled with high-strength bolts. Since then—through the sponsorship of the Research Council on Riveted and Bolted Structural Joints and the cooperation of Northwestern University, Purdue University, the University of Washington, the University of Illinois, practicing engineers, and the structural steel fabricators—many studies have been made to determine the behavior of such joints.

1. Research Assoc. Prof. of Civ. Eng., Univ. of Illinois, Urbana, Ill.
2. Bolts furnished under ASTM Designation A-325.
3. Numbers in parentheses refer to references listed in the Bibliography.

By 1952 a great many laboratory and field studies had been completed and, very appropriately, were described to the engineering profession at the Centennial Convocation of the American Society of Civil Engineers.(2,3,4,5,6 and 7) These studies included tests of the bolts themselves as well as tests of lap joints and butt joints loaded either under static conditions or repeated load conditions and in both tension and compression.

In addition to demonstrating the economy and superior quality of the high-strength bolt, the Research Council has prepared a specification entitled, "The Assembly of Structural Joints Using High Strength Steel Bolts." This specification, adopted in January 1951 and revised in February 1954, has been widely accepted by the engineering profession.

General Behavior of Bolted Joints

It has long been known that the working loads on most riveted joints are resisted by means of the frictional forces in the connections rather than shear on the rivets. Nevertheless, the design of such joints is based on the premise that the load is transferred from one portion of the member to another by means of direct shear on the rivets. In the same manner, a properly assembled joint with high-strength bolts resists loads by virtue of the friction between the connected parts. By following the procedure recommended by the Research Council, that of substituting an equal number of bolts for rivets of the same nominal diameter and installing these bolts with an initial tension at least as great as 90 per cent of the elastic proof load of the bolt material, connections are obtained which have properties generally superior to those of a similar riveted joint.

To develop the frictional resistance necessary to carry the working loads on bolted joints, a high axial tension must be maintained in the high-strength bolts at all times. To maintain this tension requires the use of hardened washers under both the head and nut of the bolt. With the hardened washers and a high initial tension, it has been found, both in the laboratory and field tests, that the bolts remain tight and the joints rigid even under the most severe loading conditions. However, it is necessary that the tension in the bolts be in accordance with the recommendations of the Research Council to obtain this superior behavior.

Some engineers have expressed concern over the possibility of slip in a high-strength bolted joint; however, those well acquainted with the behavior of such connections believe that this concern is unwarranted. Many structural members which are subjected to a stress in only one direction under both dead load and live load conditions are erected with the fasteners in bearing in this same direction. Consequently, there should be no question of slip in these connections. However, the frictional resistance of connections which are subjected to reversals of stress, must be great enough to prevent slip. For this reason, the Research Council has concentrated a large part of its effort on the determination of the conditions necessary to inhibit slip in a bolted structural joint, and in the preparation of a specification that will insure that these conditions are met.

It can be shown that, for a bolted joint of balanced design[4] and an apparent coefficient of friction of 0.25,[5] the stress in the member at slip is equal to approximately one third the unit axial tension on the nominal area of the bolts. Thus, a tension of approximately 54,000 psi would be required in the bolts to eliminate slip in a joint stressed to 18,000 psi on the net section of the connection. An axial tensile stress of this magnitude can be obtained readily in high-strength bolts which meet ASTM Designation A-325, in fact it corresponds to only about 84 per cent of the elastic proof load of the bolts. In addition, any reduction of the rivet-shear to plate-tension ratio, necessitating more or larger rivets, or increase of the coefficient of friction over the minimum of 0.25 considered above will increase the frictional resistance of a joint. Therefore, bolted structural joints which are assembled properly can be expected to perform at stresses at least as great as the normal working stresses without slipping into bearing.

Bolted Joints Subjected to Repeated Loads

Since high-strength bolts provide a joint in which the load is carried by friction rather than bearing, such joints are found to be extremely effective for members which are subjected to reversals of stress. There is little or no change in axial stress in the bolts of joints which are subjected to shear-type loadings and, consequently, the fatigue life of the bolts is very great. This is well borne out by the fact that, to date, no bolt failures have been obtained in bolted joints in which the load is carried by friction. It is important also to note that in no case have properly assembled high-strength bolts become loose even under the most severe loading conditions.

A number of recent fatigue tests have been conducted in an attempt to obtain further information concerning the behavior of bolted joints which are subjected to repeated loads and in which the bolts are loaded in either shear or tension. The results of these studies have, in part, served as a basis for the recommendations of the Research Council for the proper procedures to be followed in the assembly of high-strength bolted structural joints and will be discussed briefly in this paper.

(a) Bolts in Shear. Because of the Research Council's recommendation that high-strength bolts be torqued to at least 90 per cent of the elastic proof load,[6] some engineers have been concerned over the possibility of overtorqueing the bolts. To alleviate these fears, a short series of fatigue tests were conducted on specimens of the type shown in Fig. 1, in which the bolts were tightened far beyond the elastic limit.

Prior to the conduct of these tests, it was found that two to three turns of the nut, after it was hand tight, were required to rupture the bolts in the

4. A connection of so-called "balanced design" is one in which the parts are so proportioned that the allowable unit working stresses in all parts would be reached simultaneously. Thus, for present specifications the net tensile area for a balanced design would be 0.75 times as great as the shear area of the fasteners based on their nominal diameter (T:S equals 1.0: 0.75).
5. Tests at the University of Washington (6) and at the University of Illinois (3) have shown that the apparent frictional coefficient for properly designed bolted joints will be between 0.25 and 0.35.
6. Elastic proof loads as provided in ASTM A-325 are 28,390 lb. and 35,970 lb. for 3/4 and 7/8-in. bolts respectively.

specimen; about one and one-half turns produced the maximum axial tension that the bolts would develop and about a ten per cent reduction in the bolt area as a result of the plastic deformation that took place during the torqueing.

Four fatigue tests were conducted on specimens in which the bolts had been tensioned by rotating the nuts one and one-half turns. The results of these fatigue tests are presented in Table 1 and demonstrate that the bolts do not fail in fatigue, even under these very severe loading conditions.

All of the joints summarized in Table 1 withstood or would have withstood at least 2,000,000 cycles of loading in which the stress on the net section was $\pm$ 20,000 psi.[7] Similar riveted joints[3] when subjected to a stress of $\pm$ 18,000 psi withstood only about 600,000 cycles before failure. Thus, the large initial tension in the bolts is seen to be very effective in increasing the fatigue resistance of the connections.

These tests also help to demonstrate the desirability of having a high initial tension in the bolts to protect against slip. One of the members, Specimen BOS-2, withstood more than 2,000,000 cycles of stressing to 30,000 psi without slipping, in spite of the fact that this joint had been coated with a heavy grease before testing.

(b) Bolts in Tension. For many years, engineers have disagreed on the use of rivets and bolts in direct tension. Some have mistakenly reasoned that the tension in the fastener increases immediately upon application of an external load while others have stated that the tension does not change until the applied external load equals the total initial tension. Because of this difference of opinion and the extremely high initial tensions in the bolts of joints assembled with high-strength bolts, it was considered desirable to study the behavior of connections, such as the member in Fig. 2, in which the bolts are subjected to repeated direct tensile loads. In these repeated load (fatigue) tests, studies have been made to determine the effect of initial tension in the bolt as well as other variables on the behavior of the bolts.

The specimens for the direct tension tests were fabricated from 24-in. I-sections. Four 3/4-in. high-strength bolts (ASTM Designation: A-325) or four 3/4-in. rivets (ASTM Designation: A-141) were used to fasten the abutting flanges together. A beveled washer having a 1 to 6 slope (a slope equal to that of the I-beam flange) was placed under the head and nut of each bolt except for two specimens. In these two specimens, a flat hardened washer was placed under the head of the bolt while a beveled washer was placed under the nut, thus causing the head of the bolt to bend through an angle of approximately 10^{o} as it was torqued into position.

In the fatigue tests of the tension specimens, the behavior of the bolts was studied for various prestresses and applied loads. The prestress was varied between 0.1 and 1.2 times the elastic proof load, while the applied load was either 0.47, 0.6 or 0.9 times the elastic proof load of the bolts.

The results of the fatigue tests are presented in Table 2. In this table, the prestress is the nominal tension placed in the bolts before the fatigue tests were started. However, the actual tension in the bolts during the tests might have been somewhat less than this reported value because the bolts and washers have a tendency to slide down the flanges. The range of applied external load was from zero to the total applied load listed in the 4th column of

7. The American Railway Engineering Associations Specifications for Steel Railway Bridges allow a stress of $\pm$ 12,000 psi for members subjected to a complete reversal of stress.

Table 2. Since the maximum stress in the bolts was not always proportional to this applied load, the maximum stress is also reported and is the stress on the effective bolt area[8] as determined from elongation measurements on the bolts. All of the bolted specimens except Specimen F-3E failed by rupture of one or more of the bolts. The straight bolts (beveled washers under the heads) failed in the threads at the face of the nut, while the bent bolts in the two specimens without beveled washers under the bolt head failed at the junction of the head and the shank.

The effect of the initial tension in the bolts is readily evident from a comparison of the results of the tests on Specimens F-3E and F-1B. The maximum load applied to these specimens was the same. However, Specimen F-1B failed after only 13,400 cycles of loading while Specimen F-3E had not failed in more than 2,000,000 cycles of loading. Thus the larger prestress in the F-3E specimen provided a large increase in the resistance of the bolts to repeated loads.

A more complete picture of the effect of the initial prestress may be obtained from the S-N curves shown in Fig. 3. In this figure, the maximum stress on the effective bolt area is plotted against the number of cycles to failure. It is immediately evident that as the prestress is increased the bolts withstand increasingly larger maximum stresses for the same number of cycles to failure. The curves are not parallel but become successively flatter as the prestress is increased; thus, as the prestress increases the fatigue life becomes more sensitive to changes in maximum stress.

It may also be noted in the results of Table 2 that the fatigue life of the high-strength bolts was much greater than that of rivets tested under similar conditions. However, when the bolt head was caused to bend to the slope of the I-section flange, a very large reduction in fatigue life was obtained; it is essential that the bending in bolts used in direct tension be kept to a minimum. It is also desirable that the bolts be installed in such a manner that the washers can not slip down the sloping flanges as the members are loaded. If, for standard I-sections, the washers slip down the flanges, the bolts will lose some of their initial tension and, as a result, will be weaker under repeated loading conditions.

The tests described above as well as the many other tests which have been reported previously demonstrate the need for maintaining a high initial tension in the high-strength bolts. The loss of this tension permits a joint to slip at a much lower level of stress in a shear joint, and in bolts under tensile loading provides a much lower resistance to fatigue-type loadings. In addition, the use of the high bolt tensions in no way endangers or reduces the strength of the bolts. On the contrary, the most efficient connections have been obtained in those cases in which the bolts have been over-torqued.

Bolted Joints Subjected to Static Loads

Bolted joints which are designed in accordance with present recommendations provide for the substitution of a bolt for a rivet of equal diameter. Since the bolts are of high-strength material, any connection designed in accordance with the recommended practice will fail in the member itself rather than in the bolts. However, riveted connections often are found to fail by a shearing of the rivets.

8. The effective bolt area is the area based on a diameter equal to the average of the pitch and root diameter of the thread.

In the tests which have been conducted on bolted joints, it has been found that the ultimate static strength of the connections is not affected by the initial tension in the bolts. However, as noted previously, the fatigue strength as well as the resistance of the joint to slip depends greatly upon the clamping force of the bolts.

Several recent studies of connections fabricated with high-strength bolts are of interest in studying the strength and slip behavior of bolted joints. These studies have included tests of bolts in shear as well as tests of bolts in tension.

(a) Bolts in Shear. Two groups of tests in which the bolts were subjected to shear will be discussed briefly. The first of these concerns a test of flat plates fabricated with bolts which were over-torqued while the second group of tests concerns a study of the strength of bolted connections in large I-sections.

A specimen of the type shown in Fig. 1 and assembled with over-stressed bolts was tested statically. This specimen, being of balanced design, had a net tensile area which was only three-quarters as large as the shearing area of the fasteners. The bolts were torqued to one and one-half turns of the nut or approximately the maximum strength of the bolt material. With this extremely high initial tension in the bolts, the joint withstood a stress of approximately 27,000 psi on the net section of the plates before slipping into bearing, and an ultimate strength of 212,800 lb or 60,400 psi. It is apparent from these data that the bolt tension again did not affect the ultimate strength of the connection. However, the high bolt tension had a large retarding effect upon the slip of the connection and provided a great deal of frictional resistance.

The second group of static tests consisted of tensile tests of three large I-sections. One of the specimens was fabricated with hot-driven rivets while the other two were bolted. The general details of the specimens, designated S-1, S-2, and S-3, are shown in Fig. 4. Specimens S-1 and S-2 were fabricated with high-strength steel bolts. Specimen S-1 was assembled with hardened beveled washers between the heads of the bolts and the sloping faces of the I-beam flanges to provide parallel bearing surfaces for each bolt. However, for Specimen S-2, only flat hardened washers were used. Consequently, as the bolts for Specimen S-2 were torqued, the bolt shanks were bent through an angle of approximately 10^{o} as the bolt heads were pulled into contact with the flat washers on the sloping faces of the flanges.

The two bolted members slipped into bearing at loads of approximately 366,000 lb. This load corresponds to an average nominal shearing stress on the bolts of about 21,000 psi and, based on the initial tension in the bolts, is equivalent to an apparent coefficient of friction of about 0.40. It appears that the frictional resistance developed in the long connections of these members was somewhat greater than has been obtained in the smaller flat-plate joints reported in a number of other studies.

The results of the tests of the three large I-sections are briefly summarized in Table 3. It will be noted that the bolted members failed at loads of 798,000 lb. and 808,000 lb., and a test efficiency[9] of approximately 74 per cent. Both of these failures occurred through the net section of the I-beam. The riveted member, Specimen S-3, failed by a shearing of the rivets in one

9. The test efficiency is taken as the ultimate strength by test, divided by the theoretical strength of the gross section based on the coupon strength of the material.

connection at a load of 760,000 lb. After this initial shear failure, all of the rivets in the connection were removed and the joint was reassembled with high-strength bolts and beveled washers. The specimen was again loaded and failed in the rivets of the second connection at a maximum load of 818,000 lb. After bolting the second connection of the member, the load was again carried to failure and in this third loading the member failed in the net section at a load of 870,000 lb. This fracture load is considerably above that obtained for the two bolted members. However, it must be remembered that the material in the connection was subjected to a great deal of cold working during the first two loadings when the rivets failed in shear and may have been increased in strength by these previous loadings.

The behaviors of the bolted joints with or without beveled washers were not greatly different. Some slight differences were noted in the manner in which the joints slipped into bearing; however, the ultimate strengths were very nearly the same.

(b) Bolts in Tension. In the discussion of the fatigue tests in which the bolts were loaded in tension, mention was made of the concern of engineers over the tensile loading of bolts which are under high initial tensions. Many of the questions which have been raised can be answered by the results of the static and fatigue tests conducted on the specimens shown in Fig. 2 and the results of other tests reported in the literature.(9)

As a means of studying the behavior of bolts loaded in tension under static loading conditions, six static tests of members as shown in Fig. 2 were conducted and are summarized in Table 4. This table includes the results of tests on five bolted joints and one riveted joint. From the data, it can be seen that decreasing the prestress from 0.9 to 0.1 of the elastic proof load (25.6 to 2.8 kips per bolt) caused very little change in the ultimate strength of the bolts. Thus, the prestress in a bolt has little, if any, effect on its capacity for carrying static loads, as contrasted with its great effect upon capacity for resisting repetitive loads.

One of the most significant observations was, that the ultimate static tensile strength of the bolts was well below that which would have been calculated from the results of direct tension tests of individual bolts. On the basis of such individual tests, the ultimate loads on these specimens could have been expected to reach approximately 187,000 lb. However, the bolted members withstood ultimate loads which were only about 85 per cent this great. This decrease in the amount of applied load to rupture was caused by the prying action in the connection which results from the compression forces that develop at the toes of the flanges as the fittings deform. This prying action provides a greater load in the bolts than is applied externally. The ultimate load carried by the riveted specimen was only 120,000 lb., a value considerably lower than that carried by the bolted specimens.

The manner in which the tension developed in the bolts was studied under static loading conditions in a number of the specimens which were tested in fatigue. The results of this study are presented in Fig. 5 and show the variation in effective bolt stress with applied load. In this study it was found that the stress in the bolts did not change until the applied load had been increased to a value equal to approximately 0.6 of the initial tension. Thus, the initial tension and the applied load are not additive in the early stages of loading in these tests. The point at which these two stresses become additive does, no doubt, depend to a large extent upon the geometry and flexibility of the members connected.

CONCLUSION

In this discussion one condition stands out strongly as being essential if the connections which are assembled with high-strength bolts are to be as efficient and economical as possible: the bolts must have a high initial tension. This tension must be as high as practicable for the greatest resistance to static and fatigue loadings whether the loads are applied as shear loads or tensile loads.

It is believed that connections assembled with high-strength steel bolts will perform as well or better than comparable riveted joints, providing the bolted joints are assembled in accordance with the recommendations of the Research Council on Riveted and Bolted Structural Joints.

If the bolts are to resist direct tension loads, beveled washers should be used where bending of the bolts would otherwise occur.

ACKNOWLEDGMENTS

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TABLE 1

FATIGUE TESTS OF JOINTS WITH OVER-STRESSED BOLTS

Specimen No.	Stress Cycle on Net Section, psi	Number of Cycles to Failure of Plates
BOS-1	± 22,800	1,206,000
BOS-2**	0 to + 30,000	2,130,000*
	± 15,000	31,000*
	± 20,000	2,168,000
BOS-3	± 20,000	4,405,000
BOS-4	± 20,000	2,083,000

*Specimen did not fail. Cycle changed and test continued.

**Coat of grease placed on contact surfaces before test.

TABLE 2

SUMMARY OF RESULTS OF FATIGUE TESTS

Bolts in Tension

Specimen No.	Beveled Washer Under Bolt Head*	Total Prestress on four bolts, kips[/]	Total Applied Load, kips	Cycles to Failure	Maximum bolt Stress, psi
F-1A	Yes	11.2	68.0	9,700	42,500
F-1B	Yes	11.2	53.0	13,400	39,600
F-2A1	Yes	68.0	102.4	1,040	82,300
F-2A2	Yes	68.0	102.4	5,400	94,900
F-2B	Yes	68.0	68.0	127,600	65,000
F-2C1	Yes	68.0	53.0	189,100	64,300
F-2C2	Yes	68.0	53.0	490,000	58,600
F-3A	Yes	102.4	102.4	10,800	102,600
F-3B1	Yes	102.4	68.0	389,400	88,200
F-3B2	Yes	102.4	68.0	115,600	90,400
F-3B3	Yes	102.4	68.0	188,900	89,500
F-3C	No	102.4	102.4	1,950	------
F-3D	No	102.4	68.0	13,500	------
F-3E	Yes	102.4	53.0	+2,271,600**	82,700
F-4A1	Yes	136.0	102.4	20,900	108,300
F-4A2	Yes	136.0	102.4	24,200	106,000
F-4B1	Yes	136.0	68.0	434,600	101,300
F-4B2	Yes	136.0	68.0	471,100	102,600
F-5A	Riveted	-----	46.9	230,600	------
F-5B	Riveted	-----	46.9	1,121,200	------
F-5C	Riveted	-----	60.0	117,700	------

*Beveled washer under nut on all bolts, no washers under rivet heads.

**Specimen did not fail.

[/]Bolt tensions are equal to 0.1, 0.6, 0.9 and 1.2 of the elastic proof load.

TABLE 3

STATIC TESTS OF I-SECTIONS

Specimen No.	Load at Failure, lb	Test Efficiency, in per cent	Location of Fracture
S-1	798,000	73.9	Net section
S-2	808,000	74.9	Net section
S-3	760,000		Rivets(1)
	818,000		Rivets(2)
	870,000	80.6	Net section
Theoretical Efficiency = 83.6			

(1) Failed by a shearing of the rivets in one joint. All rivets in this joint replaced by bolts.

(2) Failed by a shearing of the rivets in the second joint. All rivets replaced by bolts.

TABLE 4

SUMMARY OF RESULTS OF STATIC TESTS

Bolts in Tension

Specimen No.	Beveled Washer Under Bolt Head*	Total Prestress on four Bolts, kips	Fastener Spacing Parallel to Web, in.	Ultimate Load, lb.
S-1	Yes	11.2	5 1/2	157,300
S-2	Yes	102.4	5 1/2	154,200
S-3	Yes	102.4	4 1/4	152,700
S-4	No	102.4	5 1/2	163,800
S-4B	No	102.4	5 1/2	169,300
S-5	Riveted	-----	5 1/2	120,100

*Beveled washer under nut on all bolts, no washers under rivet heads.

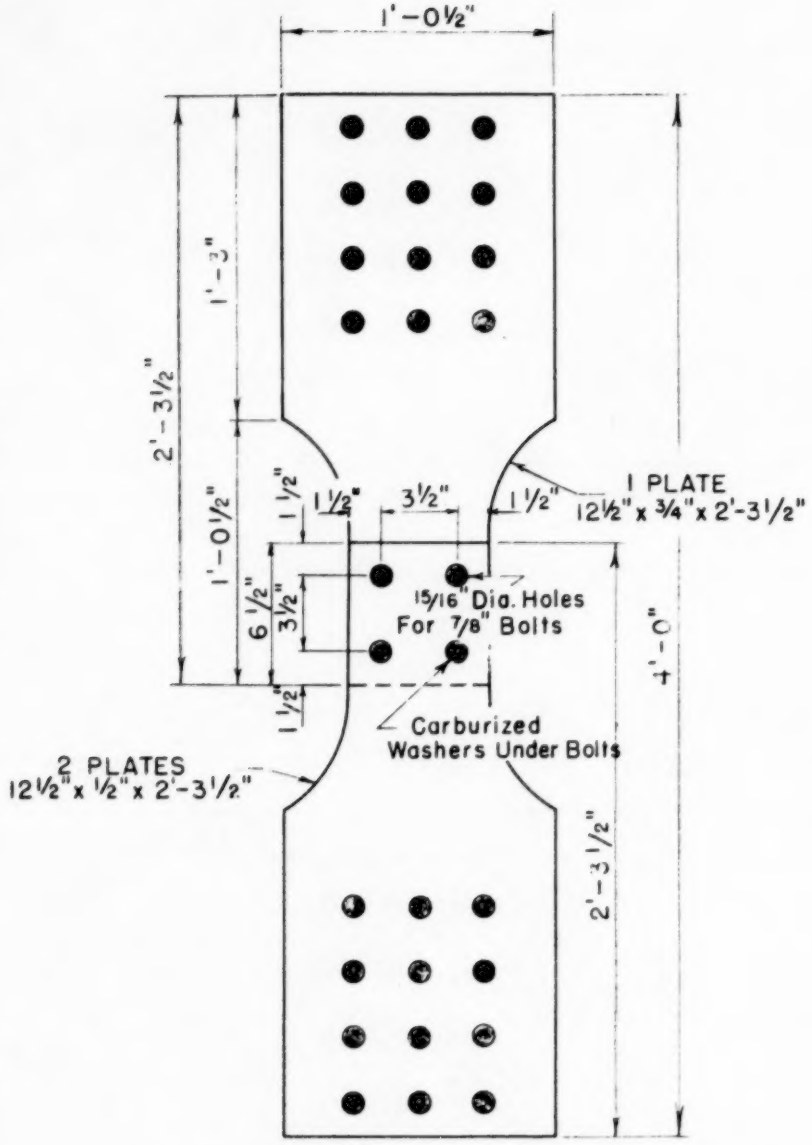
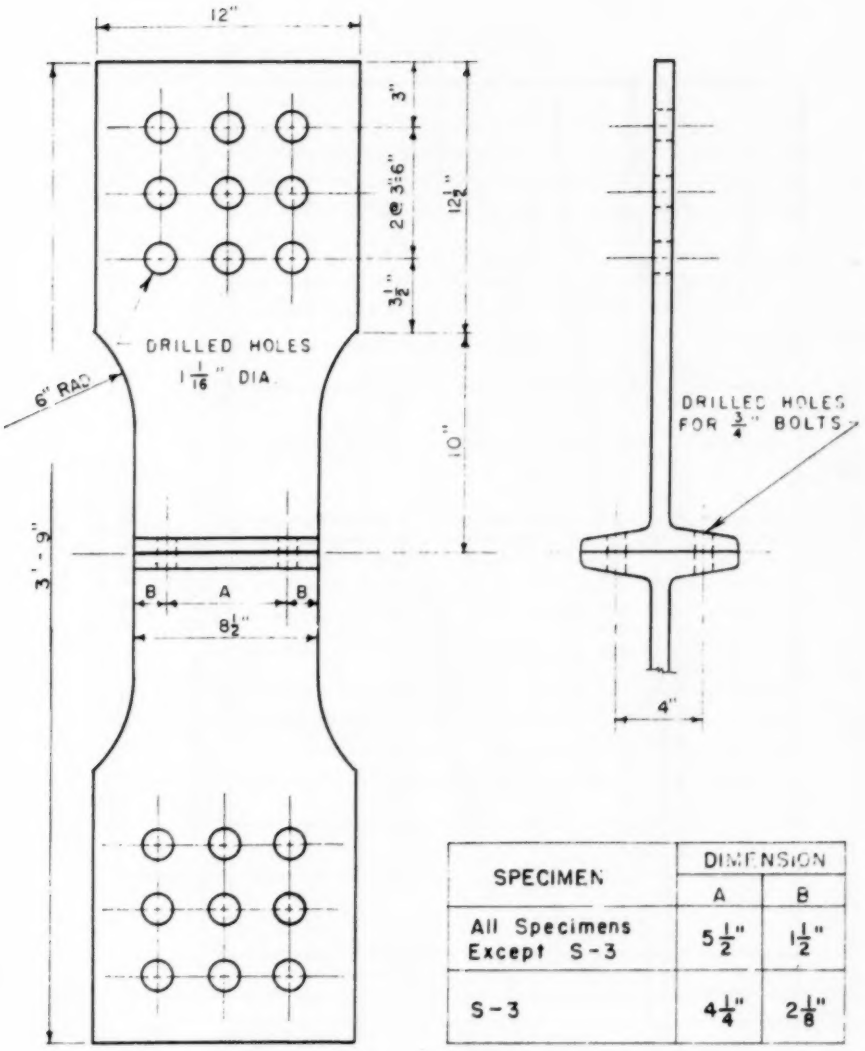


FIG. 1 BOLTED TEST SPECIMENS, BOS SERIES



SPECIMEN	DIMENSION	
	A	B
All Specimens Except S-3	5½"	1½"
S-3	4¼"	2⅛"

FIG. 2 DETAILS OF TEST SPECIMENS FOR TENSION TESTS

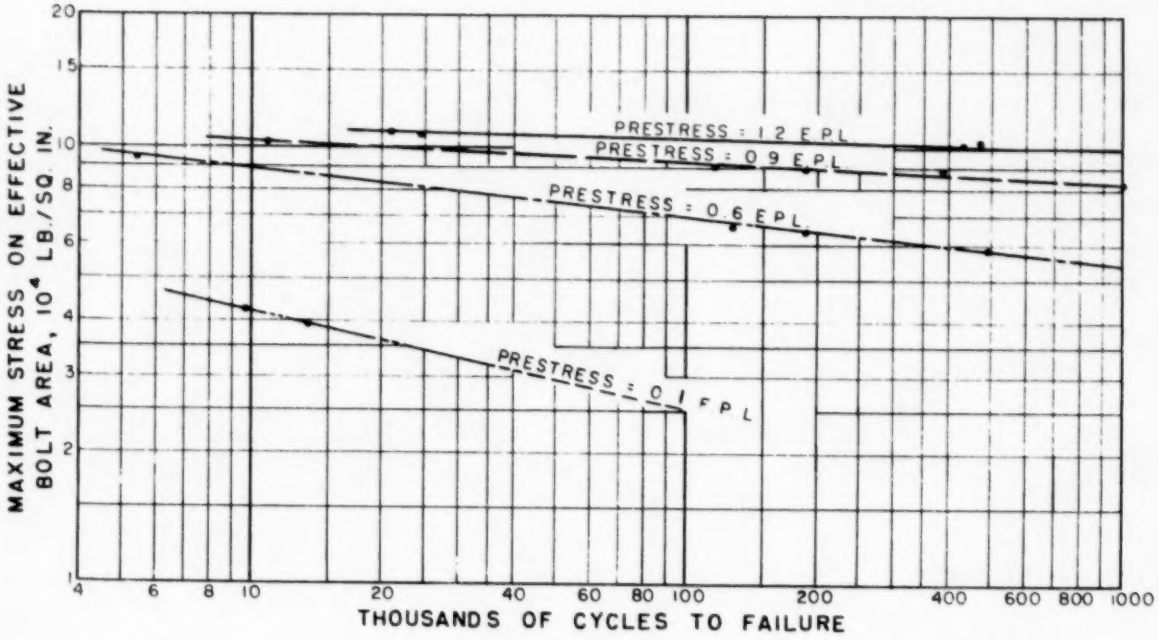
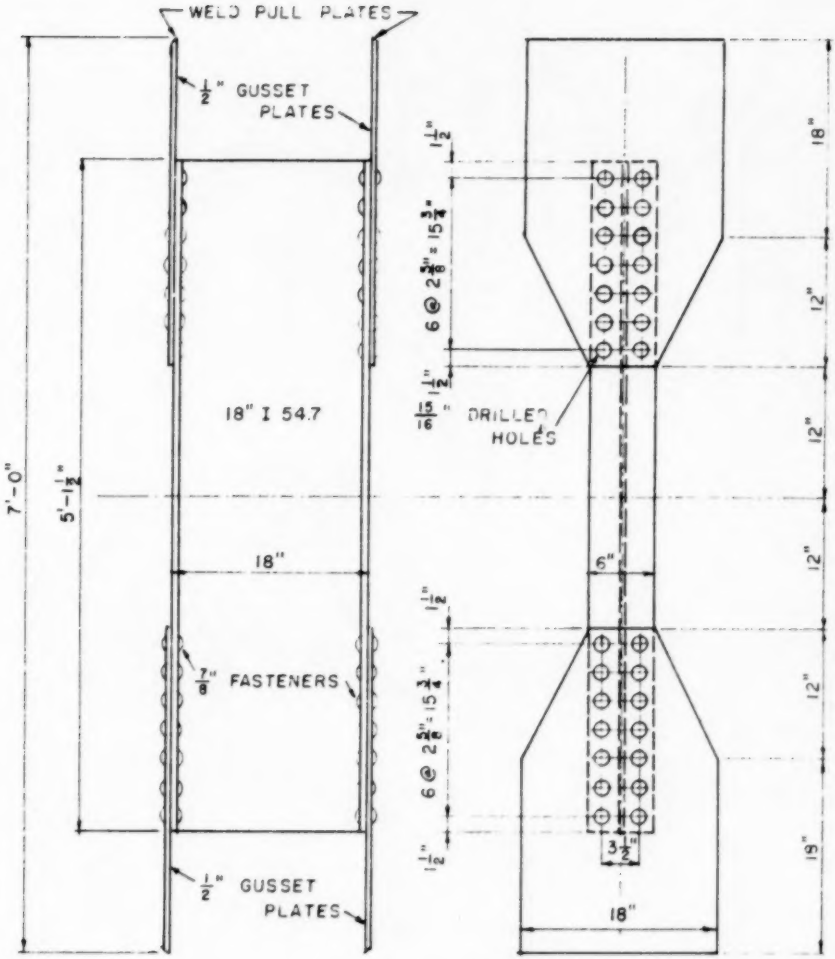


FIG. 3 S-N DIAGRAMS FOR BOLTS IN TENSION



SPECIMEN	FASTENERS
S-1	BOLTED, BEVELED WASHERS
S-2	BOLTED, PLAIN WASHERS
S-3	RIVETED

FIG. 4 DETAILS OF TEST SPECIMENS, I-SECTION TESTS

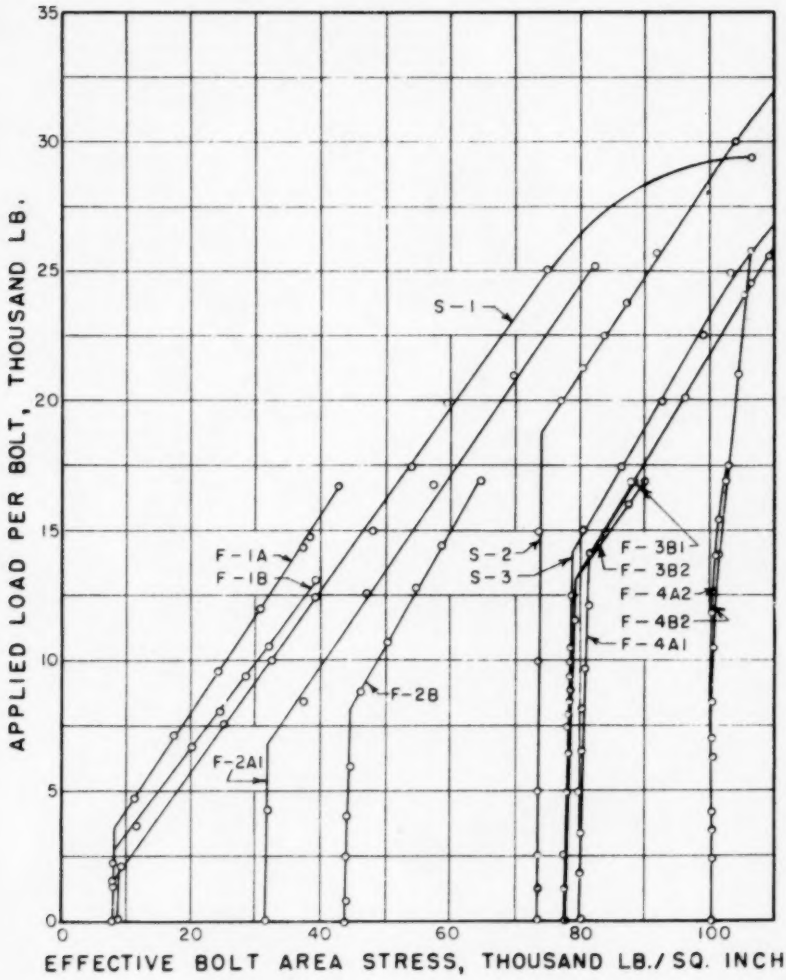


FIG. 9 VARIATION IN EFFECTIVE BOLT AREA STRESS WITH APPLIED LOAD